Widths of valleys should scale with the size of drainage area or channel size since river erosion forms valleys over geologic time and larger rivers have higher erosion potential. Consequently, valley width (as a longitudinal running average) should scale with size of drainage basins. In addition, the length scale of variability in valley width (i.e., the length of alternating canyons and floodplain segments) appears to increase with increasing drainage area, from approximately 1 km at 75 km^2, to 1 to 8 km in rivers of between 300 and 900 km^2, and up to 20 km in rivers of 8,000 km^2 (Table 1). This spatial scale of morphological variability is potentially greatest when compared to the other 6 sources of riverine heterogeneity (e.g., Figure 1). However, variations in valley widths are also controlled by landslides, earthflows, and alluvial fans. Consequently the scale of alternating canyons and floodplain reaches may not increase downstream in all rivers.

Table 1. Characteristics of alternating canyons and floodplain segments at four study sites.

Study Location (author)	Drainage Area (km^2)	Length of Floodplain Segments (km)	Separation Distance (Approx. Length of Canyons)	Morphological Effects[e]
Cascade Range, Oregon[a]	67 - 83	0.5 - 1.0	0.5 - 3.0	C, F
John Day River, Northeastern Oregon[b]	915	3 - 8	Similar scale	A, C, D
Grande Ronde River, Eastern Oregon[c]	760	1 - 4	Similar scale	A, B, E, F
Snake River, Eastern Oregon	8,400	4 - 20	Similar scale	A, B, E, F
North Fork Boise River, Idaho[d]	300 - 500	0.3 - 1.2	1 - 4.0	A, B, C, E, F

[1] Grant and Swanson (1995).

[2] McDowell (2001).

[3] Baxter (2001).

[4] Benda et al. (2003).

[5] A = increased meanders; B = increased side channels; C = finer substrate; D = more abundant and deeper pools; E = lower channel gradients; F = more terraces.

LANDSLIDES AND ROCKFALLS

Landslides that deliver large quantities of sediment to rivers can negatively impact aquatic habitats, particularly by burying channels in excess sediment (Everest et al. 1987). Large landslides (and rockfalls), however, can also create topographic knick points that can interfere with the transport of sediment and wood thereby creating habitat patches, similar to confluences and canyon mouths. Increases in sediment and wood storage upstream of landslides can trigger increases in channel meandering and formation of floodplains (Figure 8). Similarly, large earthflows (i.e., slow moving landslides) can constrict valley floors creating large upstream deposits and channel and valley widening, including enlarged floodplains (Grant and Swanson 1995). Landslides may also be significant sources of sediment that may create habitats, such as spawning areas downstream of them (Everest and Meehan 1981; Perkins 1993).

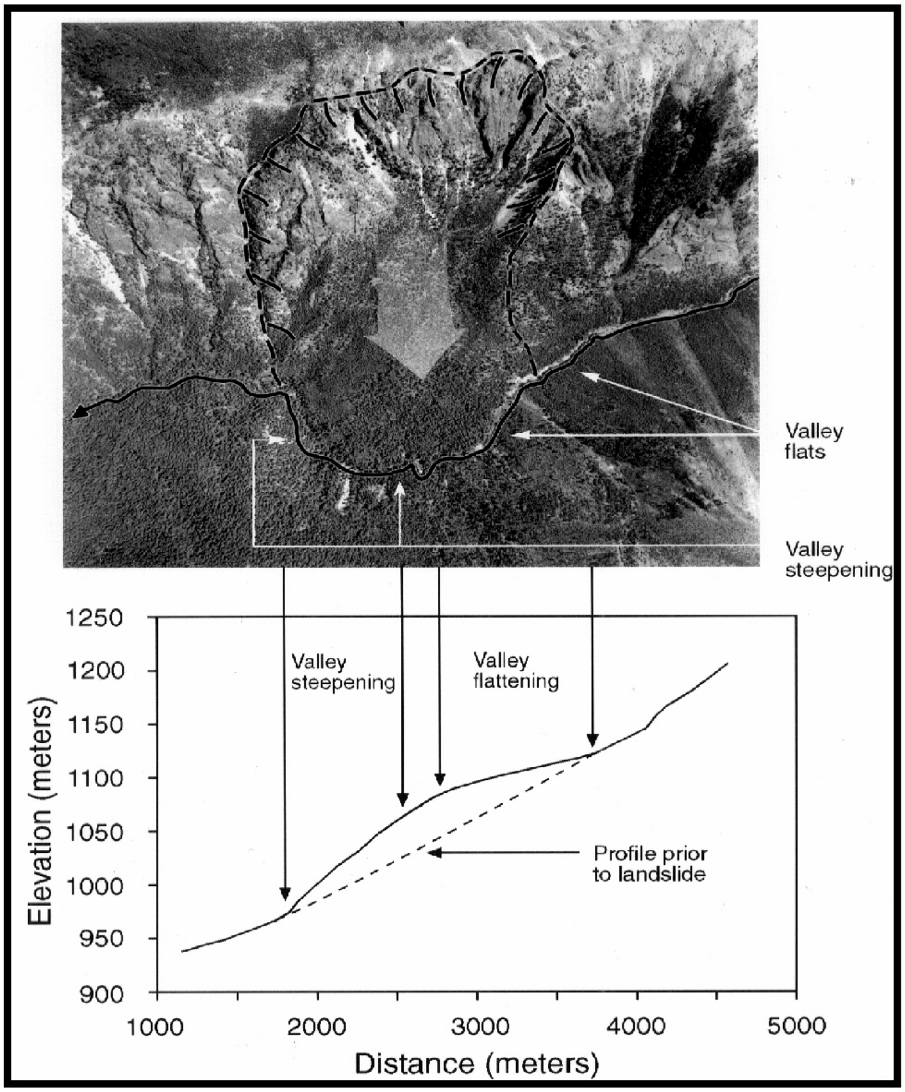

Figure 8. Large landslides can affect the morphology of channels and valley floors as illustrated in a basin located in eastern Washington. Note the effect of the deep-seated landslide on the longitudinal profile of the river, similar to a tributary junction effect (e.g., Figure 2).

The ability of landslides to affect channel morphology should depend on the size (volume) of the landslide compared to the size and energy of the receiving channel, similar to debris flows (Benda et al. 2003b) - a form of mass wasting included in the previous discussion on confluence effects because they are channelized. Hence, larger landslides should be required to affect the morphology of larger rivers and thus the size of landslides required to affect river morphology should increase downstream. There are limited field data to indicate that landslide sizes increase downstream in river systems (Miller and Cruden 2002), although the difference in spacing between landslides of different sizes remains unexplored. One hypothesis is that larger landslides are separated by an increasing distances downstream in river networks. For example, a population of landslides, characterized by numerous small ones and few large ones, is described by power laws where landslide sizes are exponentially and inversely related to their numbers (Hovius et al. 2000). Because of the size – number relationship among landslides, the distance between smaller landslides should, in general, be less compared to the distance between larger landslides in a landscape, if landslide location is random. Variations in rock type and geologic structure may also influence the spatial distribution of landslides and their sizes (Hovius et al. 1997; Selby 1985). Additional data are needed to evaluate the role of landslides as sources of habitat and physical heterogeneity in rivers.

BEDROCK OUTCROPS

Bedrock outcrops are an important source of habitat development and heterogeneity in river systems and they can interfere with the transport of water, sediment, and wood, similarly to other obstructions such as tributary fans, landslides, and canyons (e.g., Figure 1). Nevertheless, bedrock outcrops have received little attention compared to other types of obstructions, such as woody debris (Lisle 1986). Bedrock outcrops come in a variety of sizes ranging from large erosion resistant dikes to smaller random patches of channel bedrock due to limited gravel storage (Figure 9). Similar to other obstructions, bedrock outcrops have been associated with pool formation downstream of debris flow fans (Griffiths et al. 1996), pool formation proximal to alluvial/debris fans that have forced channels against opposite valley walls (Grant and Swanson 1995), and sediment deposition (Lisle 1986).

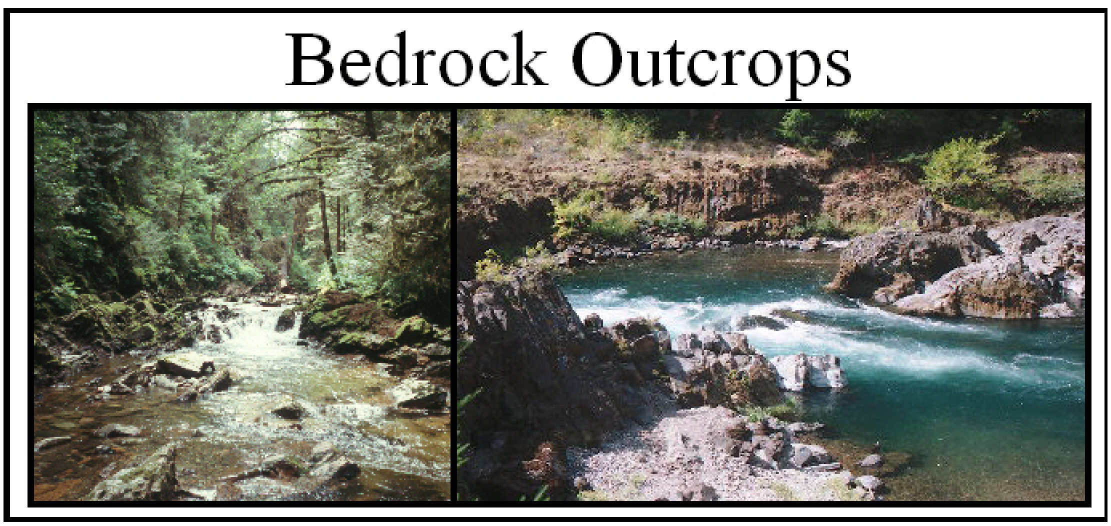

Figure 9. Examples of bedrock outcrops and their effects in rivers of different sizes.

Perhaps among all of the 7 sources of habitat heterogeneity in rivers (Figure 1), bedrock outcrops may be the most variable in size and spacing, with no apparent scaling relationship among their size, separation distance, and river size. Rather, the size and spacing of bedrock outcrops may be dependent on the local geology of a river basin that promotes the formation of outcrops as well as on erosional history, characteristics unique to any basin. In rivers that lack other sources of riverine heterogeneity, such as log jams, canyons, and large tributary confluences, bedrock outcrops may become the largest source of the non uniform distribution of habitats.

WOOD JAMS

Logs in streams and rivers, in single pieces or jams (i.e., accumulations), are well recognized morphological features in forested landscapes (Bisson et al. 1987). Log jams usually obstruct the transport of water, sediment, and other mobile pieces of wood. The convoluted flow hydraulics around logs scour pools and undercut banks (Beschta 1983), forming important aspects of aquatic habitats. Log jams also create low gradient and wide sediment deposits upstream of them (Heede 1972), similar to fan knick points, canyons, and landslides.

Wood in streams must be mobile for log jams to form. Mobile pieces of wood must be shorter than bankfull width (Lienkaemper and Swanson 1987). Consequently, an increasing proportion of all wood in streams becomes mobile with increasing distance downstream (Martin and Benda 2001). In streamside forests with a diversity of tree heights, the number of trees that can span a channel (and create a jam) must necessarily decrease downstream. A decreasing likelihood of jam formation yields an increase in inter-jam spacing downstream. In addition, the supply of wood to streams and rivers depends on length of streamside forests and therefore the size of log jams (i.e., number of pieces and likely their length) should also increase downstream (Benda and Sias 2003). A predicted pattern of larger wood jams separated by increasing distances downstream (Figure 10) have been observed in the field (Bilby and Ward 1986; Martin and Benda 2001) and predicted in model simulations (USDA Forest Service 2002), although the pattern likely breaks down in very large rivers (where all wood is transportable) or in braided river systems that may have limited capacity to transport logs.

CHANNEL MEANDERS

Channels are rarely ever straight. The directions of channels are constantly changing in time and space because various obstructions (i.e., boulders, logs, landslides, fans, bridge abutments, etc.) abruptly deflect flow into new directions. Even in the absence of obstructions, however, unsteady and non uniform flow creates sinuous channels. Once a channel sinuosity is formed it tends to maintain itself over time because channel curvature creates centrifugal forces that create secondary flow (in addition to channel parallel flow) that is directed outside towards the bend and inside toward the point bar. Consequently, pools are formed outside of bends in association with the strongest currents while point bars are created inside bends. In addition, sediment deposition and formation of riffles occur downstream of the pool and upstream of the next meander. The alternating pools and gravelly riffles that form in meandering rivers are an important source of habitats, ranging from holding habitat in pools to spawning habitat in riffles (Bisson et al. 1987).

Meander wavelength (the distance between successive bends) scale with channel width, or its surrogates discharge or drainage area (Knighton 1998) (Figure 11). In general, meander wavelength (the distance separating two consecutive bends) is equivalent to 10 – 14 channel widths (Langbein and Leopold 1968) and since discharge scales with channel width, meander wavelength should also vary as $Q^{0.5}$ (Knighton 1998). Channel meanders also form in bedrock channels given sufficient time for bedrock erosion. Because meander wavelength scales with basin size, the size and separation distance between the different habitat patches (i.e., pools and riffles) increase downstream with increasing river size. For instance, meander wavelength (and the distance separating major pools and riffles) can vary from ten meters in channels of several meters wide to greater than 10 km in kilometer-wide channels (Leopold et al. 1964).

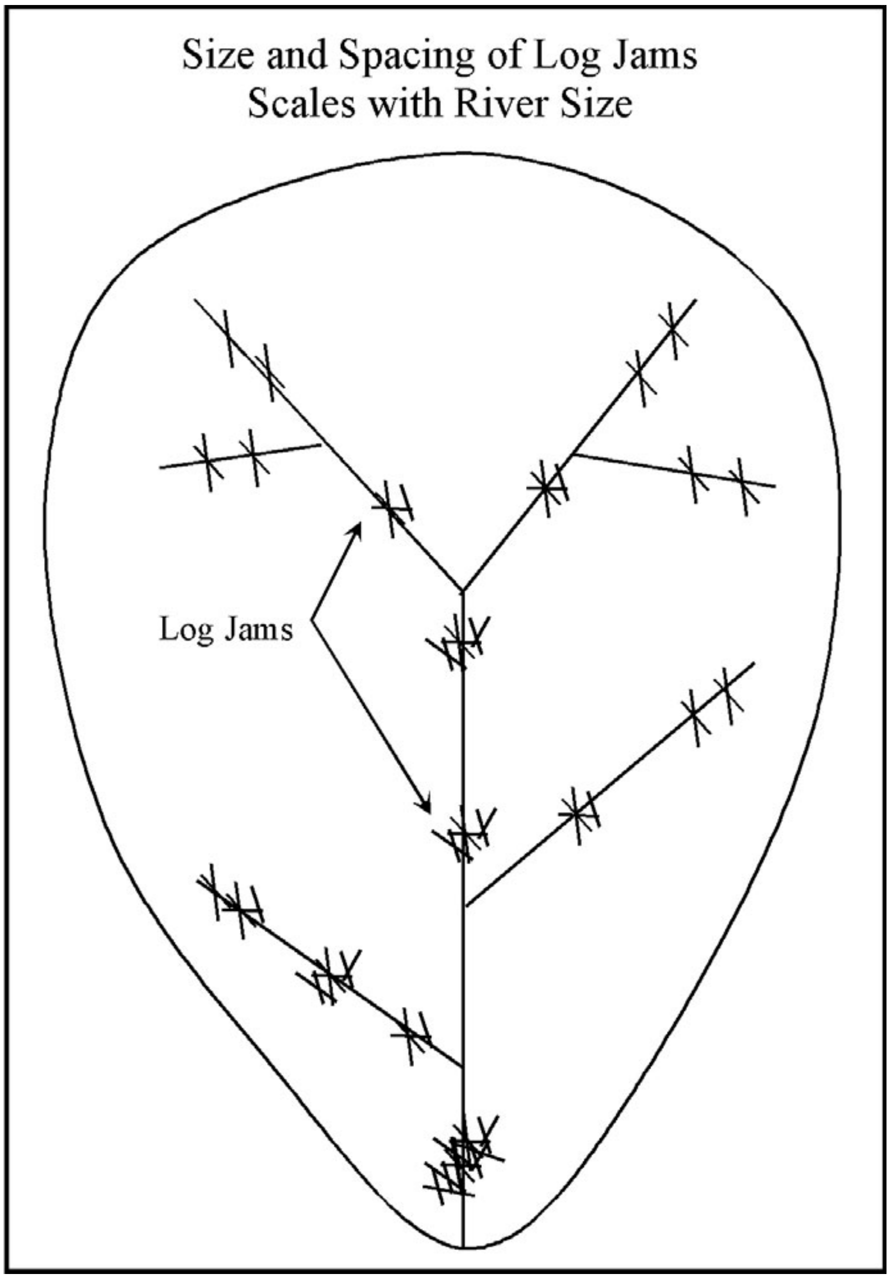

Figure 10. The size of log jams should increase downstream corresponding with an increasing distance between jams. Adapted from Benda and Sias 2003.

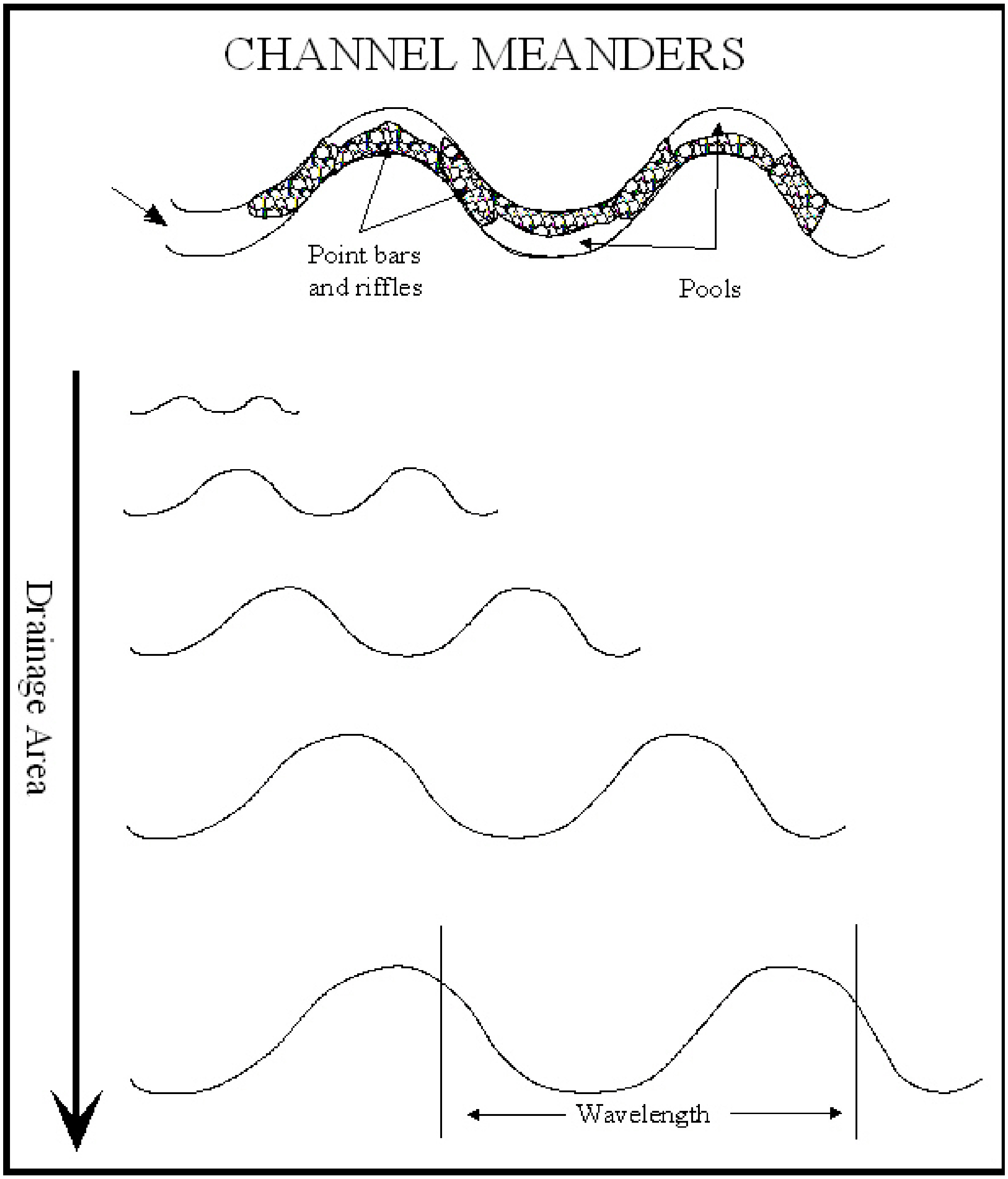

Figure 11. The wavelength of channel meanders separates pools from intervening riffles and it scales with river size, ranging from tens of meters in small channels to thousands of meters in large rivers.

BOULDER STEPS AND THEIR POOLS

Boulders are found in rivers of small to large size. The organization of boulders into distinctive boulder clusters or boulder steps, however, is generally confined to mountain streams of gradients between 0.03 and 0.15 (Grant et al. 1990). Boulder steps are formed during high flow events due to congested sediment transport when particles become clustered. Below channel gradients of approximately 0.03 streams lose their competence to transport boulders and arrange them into clusters.

Boulder steps are typically separated by “step pools”, a lower gradient and lower velocity habitat offering holding and feeding areas for species such as cutthoat trout. Spacing between steps (or step pools) is inversely correlated with channel gradient and ranges between 14 m at slopes of approximately 0.05 and 2 to 4 m at slopes of 0.15 (Grant et al. 1990). Hence, the size and scale of variation of boulder steps and their associated pools is somewhat dictated by river size, although the dependency of channel slope on particle size complicates the relationship.

THE TEMPORAL ORGANIZATION OF RIVERINE HABITATS

The temporal organization of riverine habitats refers to the frequency, magnitude, and spatial distribution of changes that occur in channel and floodplain morphology due to stochastic processes such as floods and accelerated sediment supply and transport. Moderate to large-scale fluctuations in the supply and storage of in-channel sediment and organic material due to disturbances create gullies, channels, fans, terraces, floodplains, side channels, and boulder deposits, habitats not formed during more quiescent times.

Ecologists refer to dynamic processes as “disturbances”, and they are interested in how natural fluctuations alter the physical environment and change population abundance and composition of communities through mortality and succession (Pickett and White 1985; Resh et al. 1988).

Disturbance driven punctuated inputs of sediment and wood that cause changes in channel morphology are common in hilly to mountainous terrain in North America, including in the southwestern chaparral (Rice 1973), coastal rainforests of Pacific Northwest, British Columbia, and Alaska (Dietrich and Dunne 1978; Roberts and Church 1986), Appalachian Mountains (Hack and Goodlett 1960), and in the intermountain region and southwestern highland deserts (Meyer et al. 1995; Wohl and Pearthree 1991; Kirchner et al. 2001; Istanbulluoglu et al. 2003). Consequently, natural erosion such as sheet wash, bank erosion, gullying, and landsliding triggered by fires, large storms, and floods supply the bulk of sediment within which floodplain and channel habitats are created (Benda et al. 1998). Three characteristics of the temporal organization of riverine habitats are discussed below.

First, several of the seven habitat forming features described in this paper are created only during watershed disturbances. For instance, alluvial or debris fans at confluences form, or are rejuvenated (i.e., enlarged), during periods of accelerated sediment supply to rivers (Griffiths et al. 1996; Meyer et al. 2001). Consequently, alluvial and debris fans expand and contract over time in response to disturbances, or lack of them, and the spatial extent of their upstream and downstream zones of influence should also vary over time (Figure 12, A) (Benda et al. 2003a). For example, during periods of low watershed disturbance, alluvial and debris fans and landslides may become eroded and truncated by flood flows, leading to a reduction in both their upstream and downstream effects. In contrast, during periods of heightened watershed disturbance (i.e., fires, storms, and floods), fans enlarge or landslides are triggered that impact river morphology. Moreover, landslides are triggered and logjams are created during large storms (Schwab 1998).

A second feature of channelized disturbances is that they become locally magnified in wide and low gradient reaches upstream of alluvial and debris fans, landslides, mouths of canyons, bedrock outcrops, and log jams (e.g., Figure 2). Increased channel changes occur in the vicinity of alluvial fans (Church 1983; Perkins 1993), upstream of canyons (Benda et al. 2003b), landslides (Miller and Cruden 2002), and log jams (Zimmerman et al. 1967; O'Connor et al. 2003). Increased disturbance activity at those locations could lead to increased physical heterogeneity, including greater variation in substrate size and size of floodplains, increased number of side channels, and increased age diversity of terraces and associated riparian forests (Figure 12, B).

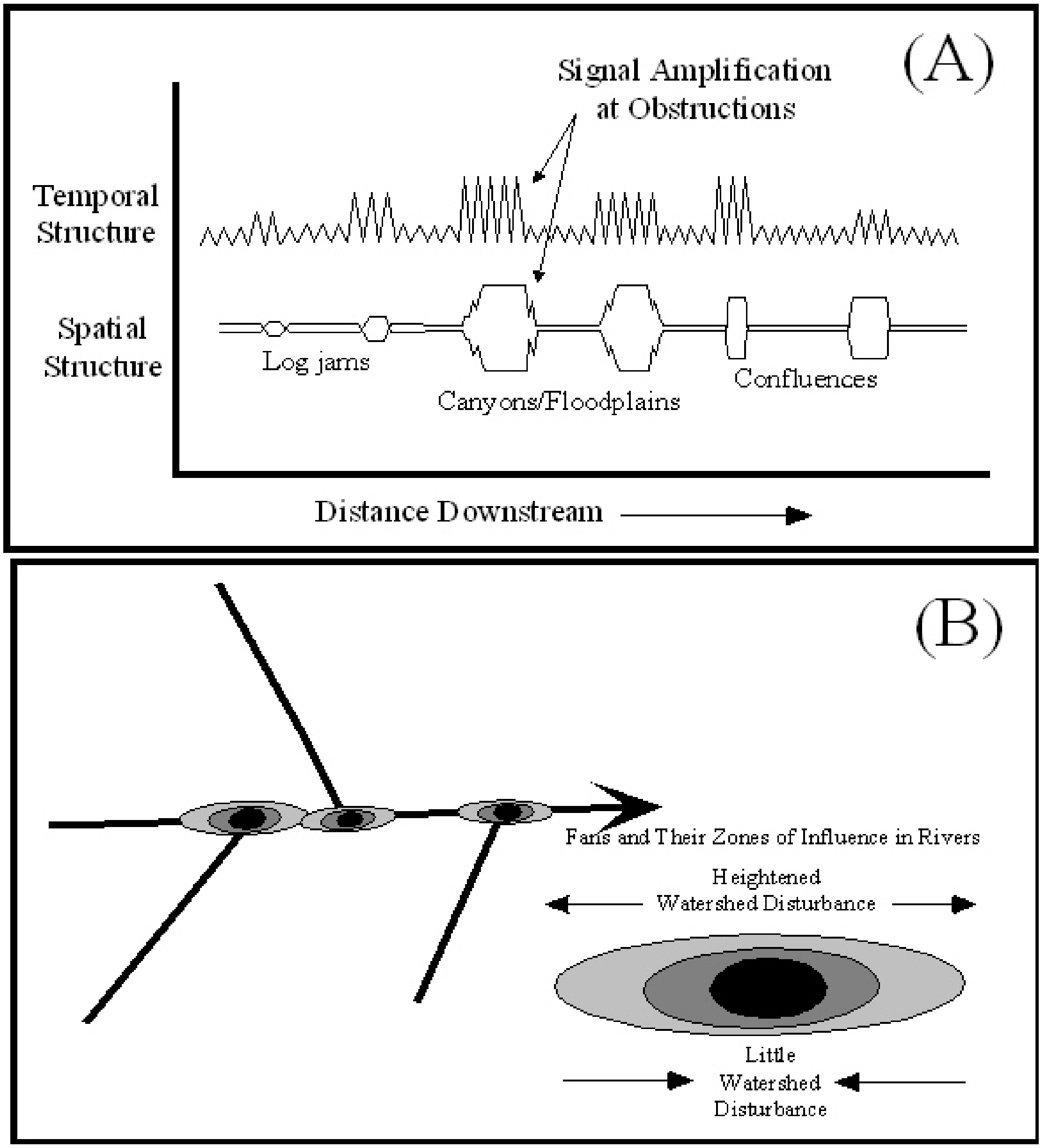

Figure 12. (A) Channelized disturbances are locally amplified near obstruction created by log jams, canyons, confluences, and landslides. (B) The zones of interference associated with various river obstructions can expand and contract depending on the state of watershed disturbance.

A third characteristic of the temporal organization of river habitats is the anticipated downstream change in channel disturbance frequency and magnitude. Periods of accelerated sediment supply and transport should increase in frequency but decrease in magnitude downstream. This pattern should arise because of 1) the size distribution of storms whereby intense storms have small spatial extent and hence affect small basins, and 2) dispersion of sediment transport downstream due to temporary storage and particle breakdown (Benda and

Dunne 1997b; Church 1998). For example, fans constructed by high magnitude flash floods or debris flows at outlets of small basins are formed during periods of accelerated sediment supply having a frequency on the order of centuries (Figure 13,A) (Benda and Dunne 1997a, Wohl and Pearthree 1991, May 2001; Meyer et al. 2003). Hence, on average at any point in time, the observed age distribution of fans at mouths of small basins should be skewed toward older features that have only minor effects on mainstem channels (Benda et al., accepted). This pattern can be locally altered in time and space by very large storms or fires that trigger widespread erosion (e.g., during hurricanes, see Hack and Goodlett 1960). In contrast, alluvial fans at mouths of larger basins are constructed by more frequent and lower-magnitude sediment pulses during floods (Figure 13, B, C). Hence, on average, the age distribution of fluvial landforms associated with fans, landslides, bedrock outcrops, and log jams located downstream in larger basins should contain a higher proportion of younger- and middle-age features.

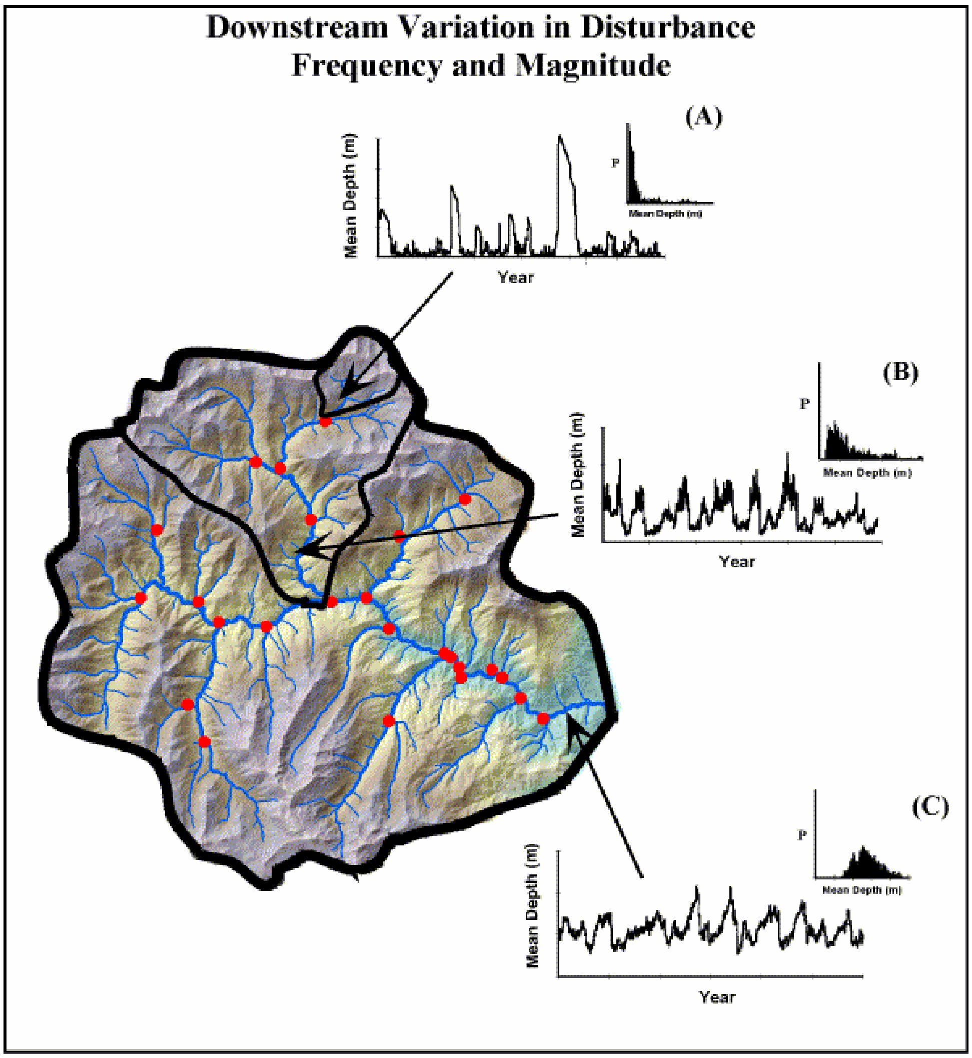

Figure 13. Frequency and magnitude of sediment-related disturbances vary with basin. (A) Disturbances are large but rare in headwaters. (B-C) Disturbances are more frequent but of lower magnitude further downstream. Adapted from Benda et al. accepted.

SCALE AND ORIGIN OF PHYSICAL HETEROGENEITY IN RIVERS

SPATIAL SCALE OF HABITAT HETEROGENEITY

The size and separation distance (i.e., spatial scale of variability) of several of the habitat forming agents varies with river size (Figure 1). For instance, the distance separating boulder steps, channel meanders, log jams, and geomorphically significant tributary confluences increases with river size and/or slope (Figure 14). Consequently, the distance separating habitat patches formed by them will be shorter in headwaters and steadily increase down valley. Although similar scaling relationships might exist between landslides and river size, there is presently insufficient field data to determine this. Moreover, the scaling relationship among bedrock outcrops, alternating canyons and floodplain segments, and river size is also not well understood. Nevertheless, physical heterogeneity (variation in morphology over some unit distance) is predicted to be greater in small streams and decrease with increasing river size.

The downstream decline in physical heterogeneity of gravel bed rivers overlays the predicted downstream change in disturbance frequency and magnitude described in the previous section. These two factors, in combination, could create a zone of maximum physical heterogeneity in river networks. First, the spacing between all 7 forms of physical heterogeneity (e.g., Figure 1) increases downstream principally because of the scaling relationship between river size and boulder clusters, river meanders, log jams, and confluences. Along this downstream gradient of heterogeneity, the temporal frequency of disturbances in the form of large magnitude sediment pulses increases with increasing basin size, although their magnitude correspondingly decreases (Figure 13). Consequently, there may be a zone in sufficiently large watersheds (order 10^2 km^2) where the relatively close spacing of riverine features overlaps with a relatively high frequency of geomorphically significant disturbances. This hypothesized zone of maximum physical heterogeneity should depend on numerous factors that may vary regionally, including watershed-specific mixtures of riverine features, regionally variable disturbance regimes, and watershed size.

There is limited field evidence supporting the hypothesized zone of maximum heterogeneity located between headwaters and larger river channels in watersheds (referred to as the "central network hypothesis"). In the unregulated Queets River (1170 km^2), Olympic Peninsula, Washington State, the largest rate of channel meandering over 40 years occurred in an area located approximately midway between the headwaters and the mouth (O'Connor et al. 2003). Channel width, number of gravel bars, and side channels were highest in the central part of the network, an area that also coincides with the highest rates of bank erosion (O'Connor et al. 2003). In another example in a large, dendritic network in the Ozark Plateau, analysis of 70 years of streambed elevation data revealed that the largest channel-bed fluctuations occurred in areas where "sediment waves combined additively…at numerous tributary confluences" (Jacobson 1995). Moreover, the greatest frequency of changes in streambed elevations occurs in mid-size watersheds (1400 – 7000 km^2), compared to channel located in smaller (< 1400 km^2) and larger (8000 – 10,000 km^2) watersheds in the same basin where perturbation frequency and magnitude were less (Jacobson 1995).

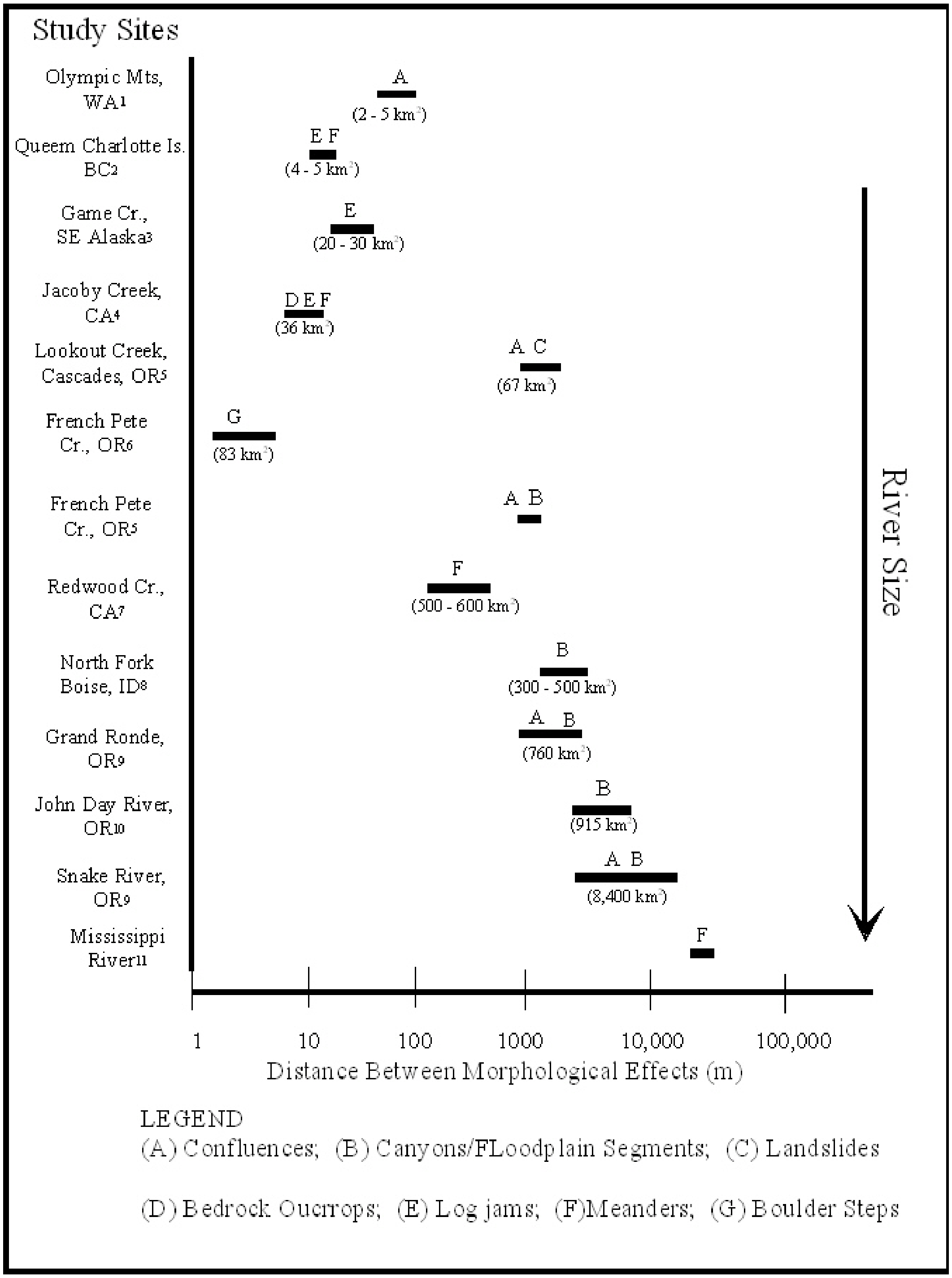

Figure 14. Studies in 13 streams and rivers that illustrate how spacing between morphological effects in channels vary according to riverine features (see legend) and river size. Overall, the spatial scale of variability (i.e., spacing between effects) increases downstream. Studies include: (1) Benda et al. 2003a; (2) Hogan et al. 1987; (3) Martin and Benda 2001; (4) Lisle (1986); (5) Grant and Swanson 1995; (6) Grant et al. 1990; (7) Madej 1999; (8) Benda et al. 2003b; (9) Baxter 2001; (10) McDowell 2001; (11) Leopold et al. 1964.

In addition to spacing, the patch size of different habitats should increase downstream in rivers for a variety of reasons. First and intuitively, larger topographic features are required to impact the morphology of larger rivers and consequently larger features impact larger stretches of river. Second, "bumps" in the longitudinal profile of rivers driven by confluences, landslides, bedrock outcrops, and log jams alter the transport and storage characteristics of channels for distances upstream of them dictated in part by the height of the "bump" and the slope of the channel. The lower the channel gradient, the greater the affected channel length, a relationship estimated by taking the cosine of the channel slope multiplied by step height. For example, a log jam of two pieces may influence a moderately steep, 5 m wide channel for only a distance of several meters but a log jam of 100 pieces in a larger, lower gradient river may create a morphological effect that extends for tens to hundreds of meters upstream.

WATERSHED TO REGIONAL VARIATIONS IN SPATIAL AND TEMPORAL ORGANIZATION OF RIVERINE HABITATS

Most streams and rivers contain some combination of the river features listed in Figure 1. Some rivers will contain all of them while others will contain only a few. In general, larger watersheds should contain a greater number of the 7 river features and hence have a higher physical heterogeneity. This arises because the heterogeneity of watershed characteristics should increase with the size of the area considered.

Each of the 7 river habitat features (Figure 1) occurs within a constraining set of watershed factors that determine their relative importance (Table 2). For instance, boulder steps, although typically limited to steep mountain streams, require a source of boulders and a means of delivering them to channels. Hence, lithology is important since boulders are more likely to form in certain types of geologies, such as marine sedimentary rocks. In addition, it is necessary to deliver boulders to channels by either debris flows or flash floods since normal runoff floods may be ineffective at moving meter-scale rocks. Channel meanders require a channel formed in sediment, although incised meanders in bedrock are also prominent in some landscapes. Log jams require a source of trees of sufficient size compared to the size of the river and hence are limited to forested landscapes (Table 2). Alternating canyons and floodplains is dependent on lithology (i.e., variable lithology may also favor increased variation in valley widths) and the occurrence of earthflows, large landslides, and large fans at confluences (Table 2). Bedrock outcrops are dependent on erosion resistant rock, such as volcanics or granitics. Tributary confluence effects reflect network geometry, network density, valley size, erosion processes, and river size.

The relative abundance and importance of the 7 riverine features should vary regionally. For instance, log jams are known to be important in the Pacific Northwest and in other heavily forested regions (Bisson et al. 1987). Log jams would be absent in streams in tundra, grasslands, or deserts. Landslides and rockfalls, alternating canyons and floodplains, and bedrock outcrops are more likely to occur in mountainous regions, such as northern California (Kelsey 1980), Oregon Coast and Cascade Ranges (Benda 1990; Grant and Swanson 1995), and Sawtooth Mountains of Idaho (Meyer et al. 2001). Likewise, landslides and rock falls should be an unimportant riverine feature in landscapes of low relief and gentle topography, such as the LTER sites of Alaska's Kuparuk River in the northern foothills of the Brooks Range and the White Mountains containing Hubbard Brook's headwater streams. In these landscapes, physical heterogeneity driven by channel meanders should dominate in the lower gradient Kuparuk River (Wollheim et al. 1999) and boulder steps and small log jams should dominate in the headwater tributaries of the Hubbard Brook (Bilby 1981).

Table 2. Watershed factors that govern occurrence of river habitat features.

River Habitat Features	Important Factors
(1) Boulder steps	Source of boulders, lithology, erosion processes, channel size
(2) Meanders	Deformable channel bed, river size, unconstrained valleys
(3) Log jams	Forests, tree size, river size, flooding regime
(4) Canyons-floodplains	Lithology, erosion processes, including earthflows, deep seated slides, tributary confluences, river size
(5) Landslides/rockfalls	Lithology, topography, erosion processes, valley size
(6) Bedrock outcrops	Lithology, topography
(7) Tributary confluences	River network geometry, network density, valley size, erosion processes, river size

CONCLUSIONS

Straight rivers with few obstructions or bends are morphologically homogeneous and ecologically less diverse. The preeminent example is regulated (diked) rivers. The most interesting and perhaps the most diverse and productive rivers are those where segment and reach-scale changes in morphology are common, driven by frequent log jams creating local sediment deposits and pools, tributary confluences forming large floodplains and side channels, or rockfalls contributing to substrate diversity. A major historical paradigm in the study of rivers relies on spatial and temporal averages, including in the River Continuum and channel classification. In this paper, we focused on variation in fluvial geomorphology and riverine habitats, rather than mean states.

Seven major features of watersheds and their river systems create aquatic and riparian habitats discontinuously along rivers. Features include tributary confluences, alternating canyon and floodplain segments, landslides, bedrock outcrops, log jams, channel meanders, and boulder clusters. Consequently, river habitats are fundamentally non-uniformly distributed. Watershed disturbances, such as fires, floods, and erosion create channel-influencing fans at junctions, landslides, and log jams, and they influence the remaining features.

They key to unraveling the spatial organization of river habitats for a variety of purposes, including defining core areas, is to define and map the spatial distribution of major habitat forming elements along river corridors. Patterns may emerge such as zones of highest physical heterogeneity located in certain parts of networks and regional variations in overall riverine heterogeneity.

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